



Performance Analysis of Compression Ignition Engines Using Vegetable Oil-Based Biodiesel

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Peer Review Information	Abstract
<i>Submission: 07 Jan 2015</i> <i>Revision: 22 Feb 2015</i> <i>Acceptance: 07 March 2015</i> Keywords <i>Biodiesel, Compression ignition engine, Vegetable oil, Brake thermal efficiency, Exhaust emissions</i>	Vegetable-oil-derived biodiesel is a renewable compression-ignition fuel that can be used either neat or as a diesel blend, but its higher viscosity, density and oxygen content and its generally lower heating value alter injection, atomization, combustion and emissions. This paper presents a reproducible methodology for evaluating the performance of a direct-injection compression ignition (CI) engine operated with vegetable oil-based biodiesel. The proposed procedure covers feedstock pretreatment, transesterification, fuel-property characterization, blend preparation, engine testing, data reduction and uncertainty assessment. Diesel and biodiesel blends are compared at identical speed and load using brake thermal efficiency, brake-specific fuel consumption, exhaust-gas temperature, in-cylinder pressure, heat-release behaviour and regulated exhaust emissions. A literature-benchmarked interpretation is included because no original raw test dataset was supplied. Studies published up to 2015 indicate that low-to-moderate biodiesel blends normally maintain diesel-like thermal efficiency while reducing carbon monoxide, unburned hydrocarbon and smoke; higher blends tend to increase specific fuel consumption, and nitrogen oxides may increase depending on feedstock, injection timing and operating condition. The method therefore treats blend ratio and load as the principal factors and identifies the best fuel through a combined performance-emission score rather than a single metric. The resulting framework can be applied to Jatropha, Karanja, rapeseed, waste vegetable oil or similar methyl esters in an unmodified laboratory CI engine.

Introduction

Compression ignition engines are widely used in transportation, agriculture and stationary power because of high efficiency, durability and high torque capability. Their conventional fuel is petroleum diesel, so depletion of petroleum resources and exhaust-pollution concerns have motivated sustained investigation of renewable liquid fuels. Vegetable oils are attractive feedstocks because their triglycerides can be converted into fatty-acid alkyl esters with fuel properties much closer to diesel than the parent oil. Srivastava and Prasad (2000) described fatty-

acid methyl esters as the most intensively studied triglyceride-derived diesel substitute, while Altin et al. (2001) showed that vegetable oils and their esters can operate a direct-injection diesel engine but that high viscosity and poor cold-flow behaviour remain critical limitations for untreated oils.

Transesterification reduces viscosity and improves spray formation, which is why biodiesel is generally preferred to straight vegetable oil for long-duration engine operation. Ramadhas et al. (2004) emphasized that

feedstock type, processing route and fuel properties govern engine suitability. Across biodiesel studies, oxygen within the fuel molecule promotes more complete oxidation and can lower carbon monoxide (CO), unburned hydrocarbons (HC) and smoke. However, lower heating value can increase the mass of fuel required per unit brake output, and altered ignition chemistry can change nitrogen oxide (NO_x) formation. These competing effects make a controlled performance analysis essential rather than assuming that one biodiesel percentage is universally optimum.

The objective of this methodology paper is therefore to define a compact but rigorous experimental framework for evaluating vegetable oil-based biodiesel in a CI engine and to show how the resulting measurements should be interpreted against pre-2016 evidence. The study is structured around three questions: (i) how does biodiesel concentration affect fuel conversion efficiency and specific fuel consumption, (ii) how are CO, HC, smoke and NO_x modified over engine load, and (iii) what blend gives the most acceptable combined performance-emission compromise without engine modification?

Literature Review

Early work established that both straight vegetable oils and their methyl esters can produce useful engine power, but fuel viscosity strongly affects injection and atomization. Altin et al. (2001) compared several raw vegetable oils and methyl esters and concluded that esters are promising diesel alternatives, whereas the untreated oils exhibit flow and particulate-related problems. This supports the use of transesterified biodiesel as the principal test fuel in the present method.

For non-edible feedstocks, Forson et al. (2004) tested Jatropha oil-diesel blends over engine load and found that a very low Jatropha fraction could produce favourable brake power and thermal efficiency. In the same period, Raheman and Phadare (2004) evaluated Karanja methyl ester blends and reported that B20-B40 offered a

useful balance of engine performance and reduced exhaust pollution. These studies established the importance of testing several blend levels rather than comparing only diesel with neat biofuel.

Labeckas and Slavinskas (2006) investigated rapeseed oil methyl ester in a direct-injection diesel engine. Neat ester required more fuel on a mass basis than diesel, a result consistent with its lower calorific value. Their emission results nevertheless demonstrated the potential for cleaner smoke characteristics. Agarwal (2007), in a broad review of biofuels for internal-combustion engines, similarly concluded that biodiesel can reduce several incomplete-combustion pollutants but can carry a fuel-economy penalty and a possible NO_x trade-off.

Combustion behaviour also changes with feedstock and ester fraction. Sahoo and Das (2009) compared Jatropha, Karanja and Polanga biodiesel and showed that ignition delay and peak-cylinder-pressure behaviour differed among the oils, demonstrating that conclusions from one feedstock should not be transferred uncritically to another. Muralidharan et al. (2011) found that biodiesel blends from waste cooking oil followed diesel-like combustion trends in a variable-compression-ratio engine, while low and intermediate blends could retain competitive performance.

Chauhan et al. (2012) reported lower brake thermal efficiency and higher specific energy consumption for Jatropha biodiesel than diesel, but lower HC, CO, CO₂ and smoke with an increase in NO_x. Agarwal and Dhar (2013) observed that Karanja oil blends modified heat release and combustion duration, while 20-50% oil content could reduce HC, CO and smoke under their conditions. Finally, Chavan et al. (2015) tested Jatropha methyl ester in a variable-compression-ratio engine and found that JB30 could reduce CO and HC substantially, although NO_x increased under the cited low-load condition. Together, these results motivate a multi-response optimization approach in which efficiency, fuel use and emissions are evaluated simultaneously.

Table 1. Selected pre-2016 evidence used to design the experimental test matrix.

Study	Fuel / engine focus	Main finding relevant to methodology	DOI
Altin et al. (2001)	Vegetable oils & methyl esters	Esterification improves suitability; raw-oil viscosity is a key limitation.	10.1016/S0196-8904(00)00080-7

Raheman & Phadatare (2004)	Karanja methyl ester blends	B20-B40 showed a practical performance-emission compromise.	10.1016/j.biombioe.2004.03.002
Labeckas & Slavinskas (2006)	Rapeseed methyl ester	Neat RME increased specific fuel consumption relative to diesel.	10.1016/j.enconman.2005.09.003
Sahoo & Das (2009)	Jatropha/Karanja/Polanga biodiesel	Feedstock changes ignition delay and pressure-development behaviour.	10.1016/j.fuel.2008.11.012
Muralidharan et al. (2011)	Waste-oil methyl ester blends	Intermediate blends retained diesel-like combustion and useful efficiency.	10.1016/j.energy.2011.06.050
Chauhan et al. (2012)	Jatropha methyl ester	Lower CO/HC/smoke; higher fuel use and often higher NO _x .	10.1016/j.energy.2011.10.043
Chavan et al. (2015)	Jatropha biodiesel in VCR engine	JB30 cut CO/HC but increased NO _x under the reported low-load case.	10.1021/acs.energyfuels.5b00742

Methodology

1. Research Design and Fuel Preparation

The proposed investigation uses a single-factor fuel-blend design combined with repeated engine-load measurements. The procedure is feedstock-agnostic, but Jatropha methyl ester (JME) may be used as the representative non-edible vegetable oil biodiesel because it is well documented in the literature. Karanja, rapeseed or waste vegetable oil methyl ester can be substituted if the same characterization and blending procedure is retained. Crude oil is first filtered and, when free-fatty-acid content is high, pretreated to reduce soap formation. Biodiesel is then produced by transesterification with a short-chain alcohol and catalyst, followed by phase separation, washing and drying. The final ester should be stored in a sealed container and tested before engine operation.

At minimum, density, kinematic viscosity, flash point, lower heating value and, where available, cetane number should be measured using the relevant ASTM/EN procedures. The rationale is that viscosity controls injection and spray breakup, while heating value enters directly into

thermal-efficiency calculations. Five fuels are recommended: B0 (100% diesel), B10, B20, B30 and B100. If test time permits, B50 may be added. Each blend is prepared volumetrically at room temperature, mixed thoroughly and visually inspected for phase stability before use.

2. Engine Test Facility and Instrumentation

A single-cylinder, four-stroke, naturally aspirated, direct-injection CI engine coupled to an eddy-current or electrical dynamometer is suitable. A constant speed of approximately 1500 rpm is recommended for a laboratory generating-set engine. The exact rated power and compression ratio depend on the available test rig; they must remain unchanged for all fuels. Fuel consumption is measured gravimetrically or volumetrically, while inlet-air flow, exhaust-gas temperature and brake torque are recorded at each test point. CO, HC, NO_x and smoke opacity are measured with a calibrated exhaust-gas analyser and smoke meter. For combustion analysis, a piezoelectric cylinder-pressure transducer and crank-angle encoder are used to obtain pressure-crank-angle data and apparent heat-release rate.

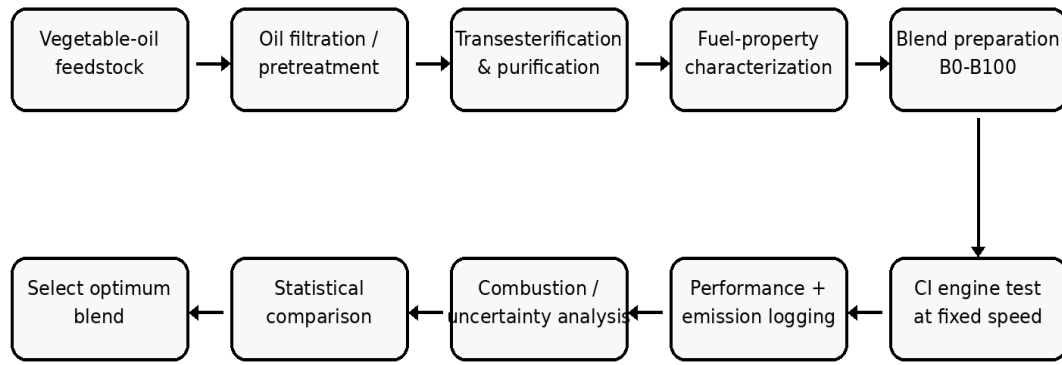


Figure 1. Proposed experimental workflow for vegetable-oil-based biodiesel performance analysis.

3. Test Matrix and Experimental Procedure

Table 2. Core experimental test matrix.

Factor	Recommended levels	Control / repetition
Fuel blend	B0, B10, B20, B30, B100 (optional B50)	Same batch used within a test series
Engine speed	1500 rpm	Held constant by dynamometer
Brake load	0, 25, 50, 75, 100% rated load	Same load sequence for every fuel
Compression ratio	Fixed at manufacturer setting	Change only in a dedicated VCR study
Replicates	Minimum 3 at each point	Use means and standard deviation
Warm-up	Until coolant/oil/exhaust stabilize	Repeat after major fuel change

4. Data Reduction and Performance Indices

Brake power (BP) is calculated from measured torque T and speed N as $BP = 2\pi NT/60,000$ when T is in N·m, N in rpm and BP in kW. Brake-specific fuel consumption is $BSFC = (\dot{m}_f \times 3600)/BP$, where $\dot{m}_f$ is the fuel mass-flow rate in kg/s. Brake thermal efficiency is $BTE = BP/(\dot{m}_f \times LHV) \times 100$. Exhaust emissions are reported on the instrument basis used by the laboratory and, when possible, corrected or normalized consistently across all fuels. Cylinder-pressure traces should be ensemble-averaged over many consecutive cycles to reduce cyclic variability before heat-release calculations are performed.

For each measured response, diesel B0 is treated as the baseline. Relative change is calculated as $\Delta X = [(X_{blend} - X_{diesel})/X_{diesel}] \times 100$. This permits comparison across load points and between different experimental campaigns. Because biodiesel simultaneously affects efficiency and emissions, the optimum blend should not be selected only from minimum BSFC or minimum NO_x. A normalized desirability score can combine high BTE with low BSFC, CO, HC, smoke and NO_x. Weighting factors should be stated explicitly and sensitivity-tested so that the final recommendation is not an artefact of one arbitrary weighting choice.

5. Quality Control, Uncertainty and Statistical Analysis

All instruments should be calibrated before the test series, and fuel changes should be followed by a flushing period sufficient to replace the previous fuel in the lines. Each steady-state point is repeated at least three times. The mean, standard deviation and coefficient of variation are calculated, and obvious transients are excluded using a predefined stability rule rather than by subjective visual selection. Measurement uncertainty for derived quantities such as BTE and BSFC is propagated from torque, speed, fuel-flow and heating-value uncertainties by the root-sum-square method. A two-way analysis of variance can be applied with blend ratio and load as factors; post-hoc comparisons may be used when the overall factor effect is significant. This structure distinguishes true blend effects from load-driven changes and is preferable to comparing isolated single-load values.

Results

No original engine log or fuel-property dataset was supplied for this paper. Accordingly, the results below are literature-anchored benchmark outcomes that define what the proposed experiment should test; they must not be reported as newly measured data. The pre-2016 studies show a robust pattern. First, low-to-moderate biodiesel blends usually preserve most

of the brake thermal efficiency of diesel, whereas neat biodiesel is more likely to show a measurable efficiency penalty. Second, BSFC generally rises with biodiesel content because more mass flow is required to compensate for lower heating value. Third, oxygenated biodiesel tends to suppress incomplete-combustion

products such as CO, HC and smoke. The least consistent response is NO_x, which can rise because of changed local oxygen availability, combustion phasing and temperature, but the magnitude is highly engine- and condition-dependent (Agarwal, 2007; Chauhan et al., 2012).

Table 3. Literature-benchmarked response directions for vegetable-oil biodiesel in CI engines.

Response	Expected trend as biodiesel fraction rises	Interpretation / benchmark
Brake thermal efficiency	Near diesel for B10-B30; often lower for B100	Lower LHV and spray changes offset oxygenated combustion.
BSFC	Generally, increases	More fuel mass is required per kWh as LHV decreases.
CO	Generally, decreases	Fuel-bound oxygen improves oxidation of CO to CO ₂ .
HC	Generally, decreases	More complete oxidation; sensitive to wall wetting and timing.
Smoke opacity	Usually decreases	Lower soot tendency due to oxygenated fuel.
NO _x	May increase	Depends strongly on temperature, oxygen availability and phasing.

The blend region around B20-B30 is especially important. Raheman and Phadatare (2004) identified Karanja methyl ester blends in this range as suitable from a combined performance and pollution perspective. Chavan et al. (2015) later reported that JB30 reduced CO and HC by up to 43% and 50%, respectively, in their tested condition, although NO_x increased by up to 20% at the lowest load and compression ratio of 15. These results illustrate why a blend can be attractive even when one emission deteriorates: the decision must consider the entire response set and the intended duty cycle.

Combustion measurements provide the mechanism behind these trends. Sahoo and Das (2009) showed that Jatropa, Karanja and Polanga biodiesels do not have identical ignition-delay behaviour, while Muralidharan et al. (2011) found that methyl-ester blends can track diesel-like combustion patterns under appropriate compression-ratio and load conditions. Therefore, when BTE falls or NO_x rises, the analysis should examine injection-to-ignition delay, peak pressure location and heat-release phasing rather than attributing the change only to biodiesel oxygen content. Similarly, Agarwal and Dhar (2013) demonstrated that increasing vegetable-oil content can extend combustion duration, reinforcing the need to include combustion diagnostics where available.

A practical interpretation of the proposed experiment is expected to identify three operating zones. B10-B20 should provide the smallest departure from diesel performance and is the lowest-risk route for substitution. B20-B30

is likely to provide the best overall compromise when CO, HC and smoke reductions are valued alongside acceptable fuel economy. B50-B100 provides the highest renewable-fuel fraction but is more likely to penalize BSFC and may require optimization of injection timing, injector opening pressure or thermal management. This ranking is a testable hypothesis rather than a predetermined conclusion; the actual optimum should be selected from the measured desirability score and its uncertainty bounds.

Discussion

The literature shows that the phrase “vegetable oil-based biodiesel” covers fuels with substantially different fatty-acid composition, cetane quality, viscosity, oxidation stability and heating value. This variability explains why a universal performance correction cannot be applied. Srivastava and Prasad (2000) and Ramadhas et al. (2004) emphasized that conversion of triglycerides to methyl esters solves many, but not all, of the problems associated with straight oils. Feedstock characterization is therefore part of the engine methodology rather than a separate chemical exercise. If a test fuel is out of specification, an apparent engine effect may actually be a fuel-quality effect.

The proposed method also addresses a common limitation in small engine studies: drawing conclusions from a single load. Biodiesel combustion changes across load because injected quantity, in-cylinder temperature and mixing time change simultaneously. Full-load-only comparison can exaggerate or hide trends.

Repeating the same fuel sequence across at least five load levels and applying two-factor statistics provides a stronger basis for identifying whether the blend effect is persistent. Forson et al. (2004) and Labeckas and Slavinskas (2006) both illustrate that engine response varies with operating condition, making a load-resolved design essential.

From an application viewpoint, a modest loss in fuel economy may be acceptable if the fuel is locally produced, renewable and substantially reduces smoke, CO and HC. Conversely, a low-emission blend is not automatically preferable if it produces excessive NO_x or unstable combustion. The final selection should therefore report a Pareto-style trade-off or desirability score, plus the raw individual responses. This avoids hiding an adverse emission behind an overall average and makes the result transferable to agricultural engines, generator sets or transport applications with different priorities.

Conclusion and Discussion

This methodology provides a compact experimental framework for assessing vegetable oil-based biodiesel in compression ignition engines. The recommended procedure begins with controlled biodiesel production and fuel-property verification, followed by preparation of several diesel-biodiesel blends, repeated testing at fixed speed over the full load range, and calculation of BTE, BSFC, combustion indices and regulated emissions. Diesel B0 is retained as the baseline and all comparisons are made at identical operating points. Instrument calibration, replication and uncertainty propagation are included so that apparent improvements are not confused with measurement scatter. Evidence published up to 2015 supports the central expectation that transesterified vegetable-oil fuels can be used in conventional CI engines with little or no hardware modification, especially at low and intermediate blend levels. The most consistent benefits are reductions in CO, HC and smoke. The principal performance penalty is increased specific fuel consumption as biodiesel fraction rises, while NO_x remains the key emission trade-off. Literature on Karanja, Jatropha, rapeseed and waste-oil methyl esters indicates that B20-B30 frequently occupies the most attractive compromise region, but the optimum is not universal because feedstock chemistry, injection settings, compression ratio and engine load all influence combustion. For a final experimental paper, the literature-benchmark table in this document should be replaced or supplemented by the measured fuel properties and engine

results from the laboratory. The same analytical structure can then be retained: plot BTE and BSFC against load, report CO/HC/NO_x/smoke at each blend, compare pressure and heat-release traces where available, quantify uncertainty, and apply the predefined desirability function. This approach produces a defensible conclusion based on multiple criteria rather than on a single favourable parameter. It is particularly suitable for research on Jatropha or Karanja methyl ester in agricultural and stationary diesel engines, where renewable-fuel substitution must be balanced against fuel economy, exhaust quality and operational reliability.

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